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The US Air Force is operating a large fleet of aging aircraft. Some examples of problems that aging aircraft can encounter are fatigue and corrosion. Throughout the Air Force and industry, many research efforts are being conducted to deal with the aging aircraft problems. Many of these efforts require a significant amount of fatigue testing, both constant amplitude testing, which can be relatively fast, and spectrum fatigue testing, which can take a significant amount of testing and inspection time.One of the main objectives of this research effort was to determine whether spectrum truncation has a noticeable effect on crack growth rates. In order to save valuable testing time, the duration of spectrum fatigue tests can be shortened by truncating the spectrum. When truncating a spectrum, small fatigue cycles that are not expected to contribute to the overall crack growth life of the specimen or structure, can be removed from the spectrum. By doing so, a significant amount of test time can be saved. It is very important though that by excluding these small fatigue cycles from the spectrum, the overall crack growth behavior will not change. Another important objective of this effort was to verify that the insertion of marker loads into a fatigue spectrum has no or a negligible effect on the crack growth rate when compared to a fatigue test without the marker loads. When running a fatigue test to determine crack growth rates, regular inspection is necessary to check the crack size versus cycle count, which can be very time consuming and might prevent running tests overnight. When inserting marker loads in a fatigue test, the test can be

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The Effects of Truncation and Marker Loads on Spectrum Fatigue Crack Growth

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Coordination and Approval

This article, *The Effects of Truncation and Marker Loads on Spectrum Fatigue Crack Growth*, is presented as a competent treatment of the subject, worthy of publication. The United States Air Force Academy vouches for the quality of the research, without necessarily endorsing the opinions and conclusions of the authors. Therefore, the views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the US Government.

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The report has been reviewed and is approved for publication.

SCOTT A. FAWAZ, Lt Col, USAF — 3 May 2005
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Abstract

The US Air Force is operating a large fleet of aging aircraft. Some examples of problems that aging aircraft can encounter are fatigue and corrosion. Throughout the Air Force and industry, many research efforts are being conducted to deal with the aging aircraft problems. Many of these efforts require a significant amount of fatigue testing, both constant amplitude testing, which can be relatively fast, and spectrum fatigue testing, which can take a significant amount of testing and inspection time.

One of the main objectives of this research effort was to determine whether spectrum truncation has a noticeable effect on crack growth rates. In order to save valuable testing time, the duration of spectrum fatigue tests can be shortened by truncating the spectrum. When truncating a spectrum, small fatigue cycles that are not expected to contribute to the overall crack growth life of the specimen or structure, can be removed from the spectrum. By doing so, a significant amount of test time can be saved. It is very important though that by excluding these small fatigue cycles from the spectrum, the overall crack growth behavior will not change.

Another important objective of this effort was to verify that the insertion of marker loads into a fatigue spectrum has no or a negligible effect on the crack growth rate when compared to a fatigue test without the marker loads. When running a fatigue test to determine crack growth rates, regular inspection is necessary to check the crack size versus cycle count, which can be very time consuming and might prevent running tests overnight. When inserting marker loads in a fatigue test, the test can be run continuously. The crack growth history can then be reconstructed after final failure of the specimen from the groups of striations, created by the marker spectrum, that are left on the crack surface.

Results from the 4" wide 7075-T651 specimens, 0.5" thick, with an EDM notch showed crack growth data that tended to indicate that truncation of the spectrum had some crack growth reducing effect. However, since the starter notch was quite large, only up to 15% of one aircraft life time could be tested. Crack growth became non-linear as the crack size grew over 50% of the specimen width and differences between the full and truncated spectrum specimens became more significant. Results from these tests did not allow for a conclusive decision on whether specimen truncation had a crack growth altering effect.

Testing of additional 2" narrow 7075-T651 specimens, 0.5" thick, with a small drill hole and corner crack allowed for testing over a larger crack growth life, up to 1.2 aircraft life times. Although only a limited amount of material was available for testing, and no data was obtained in the short crack regime (crack length on the order of the grain size), the data in the long crack regime showed no noticeable effect as a result of spectrum truncation.

Testing of 4" wide 2024-T351, 0.25" thick, specimens showed no significant effect of spectrum truncation on crack growth, even after testing well over 1 aircraft life time. Marker loads that were introduced in the full spectrum showed only a negligible effect on crack growth. However, marker loads that were introduced in the truncated spectrum showed a larger effect on crack growth.

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1. Introduction

The US Air Force is operating a large fleet of aging aircraft. Some examples of problems that aging aircraft can encounter are fatigue and corrosion. Throughout the Air Force and industry, many research efforts are being conducted to deal with the aging aircraft problems. Many of these efforts require a significant amount of fatigue testing, both constant amplitude testing, which can be relatively fast, and spectrum fatigue testing, which can take a significant amount of testing and inspection time.

In order to save valuable testing time, the duration of spectrum fatigue tests can be shortened by truncating the spectrum. When truncating a spectrum, small fatigue cycles that are not expected to contribute to the overall crack growth life of the specimen or structure, can be removed from the spectrum. By doing so, a significant amount of test time can be saved. It is very important though that by excluding these small fatigue cycles from the spectrum, the overall crack growth behavior will not change. One of the main objectives of this research effort was therefore to determine whether the particular truncation used here had any effects on the crack growth rates of the specimens.

When running a fatigue test to determine crack growth rates, regular inspection is necessary to check the crack size versus cycle count, which can be very time consuming and might prevent running tests overnight. When inserting marker loads in a fatigue test, the test can be run continuously. The crack growth history can then be reconstructed after final failure of the specimen from the striations that are left on the crack surface. It is essential however to verify that the crack growth from the marker loads have no or a negligible effect on the crack growth from the fatigue test itself, which was therefore also one of the main objectives of this research.

2. Spectrum Information and Specimen Design

2.1 Spectrum, Truncation and Marker Loads

The spectrum that was under investigation during this research was an upper wing skin spectrum for the E-8C Joint Star (B707), see Figure 1. Both the loading conditions for wing stations WS 320 and WS 360 were tested, see Figure 2 for the specific locations of these two wing stations.

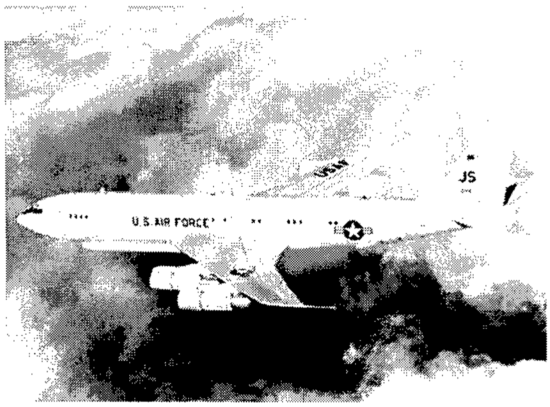

Figure 1: The E-8C Joint Star reconnaissance aircraft

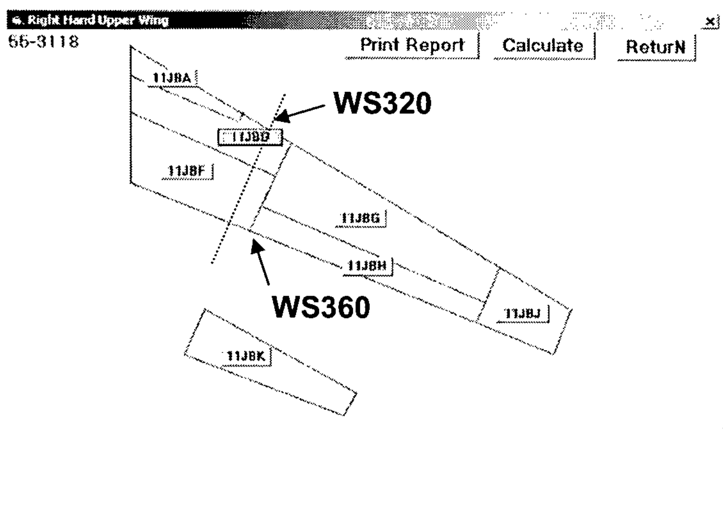

Figure 2: Wing panel locations for B707

The spectrum is normalized such that the maximum load in tension corresponds to 1.0. Since the wing loading is modeled by a simple wing bending model, the difference between the spectra for the two wing station locations is only a multiplication factor. For WS 360, the multiplication factor was 14.24, more inboard for WS 320, the multiplication factor becomes 16.8. These multiplication factors are actually the absolute stress level that are required for each win station in ksi: 14.24 ksi (98.18 MPa) for WS 360, and 16.8 ksi (115.83 MPa) for WS 320.

The spectrum is split up in blocks or spectrum passes. A spectrum fatigue life time is constructed by repeating these passes, 10 repeats are necessary to achieve on full 20,000 hour aircraft life time.

For the full spectrum, without truncation, there is a total of 937,441 segments per block or pass. Truncation was 10% on positive peak valley pairs and 25% on the negative peak-valley pairs, as recommended by Northrop Grumman. This resulted in a total of 263,707 segments per block, a significant reduction.

Note however, that the reduction in testing time is not necessarily linear with the reduction in number of cycles. Spectrum tests are typically run in a load ramp rate controlled manner, which means that by eliminating small peak-valley pairs, the time reduction is smaller than when eliminating large peak-valley pairs. Also note that time reduction is dependent on the actual cross sectional area of the specimen, since a larger cross sectional area requires larger loads to obtain the same stresses.

Marker loads were introduced into both the full spectrum block as well as the truncated spectrum block as follows: after each peak tensile stress in the spectrum which occurs only once each block (the +1.0 value in the normalized blocks), the following peak loads were introduced (numbers are fraction of the 1.0 peak tensile load):

100 cycles of 0.64
10 cycles of 0.8
100 cycles of 0.64
10 cycles of 0.8
100 cycles of 0.64
10 cycles of 0.8
100 cycles of 0.64
10 cycles of 0.8
100 cycles of 0.64
10 cycles of 0.8
1 cycle of 0.999
100 cycles of 0.64

After which the remaining part of the block is continued. The lower load point of each segment was 0.05, for a total of 1300 inserted segments.

By introducing the marker loads, the total number of segments became 938,741 segments for the full spectrum block, and a total number of 265,007 segments for the truncated spectrum block.

2.2 Specimens

Several different specimen configurations were tested in order to cover different parameters. The next paragraphs will show more details for each of the specimen configurations.

2.2.1 Wide 7075-T651 Specimens with Diamond-Shaped EDM Notch, 0.5" Thick

The first set of specimens was used to verify that the truncation of the spectrum does not significantly affect the crack growth results.

A total of 8 four-inch-wide specimens, WDS-1 through WDS-8, were tested. These specimens were designed by FASIDE at the University of Utah. The starter notch was a diamond-shaped EDM notch. The specimens were made out of 0.5" thick 7075-T651 bare aluminum. The gage length was 6". Figure 3 shows the drawing with the exact dimensions. Table 1 shows the test matrix.

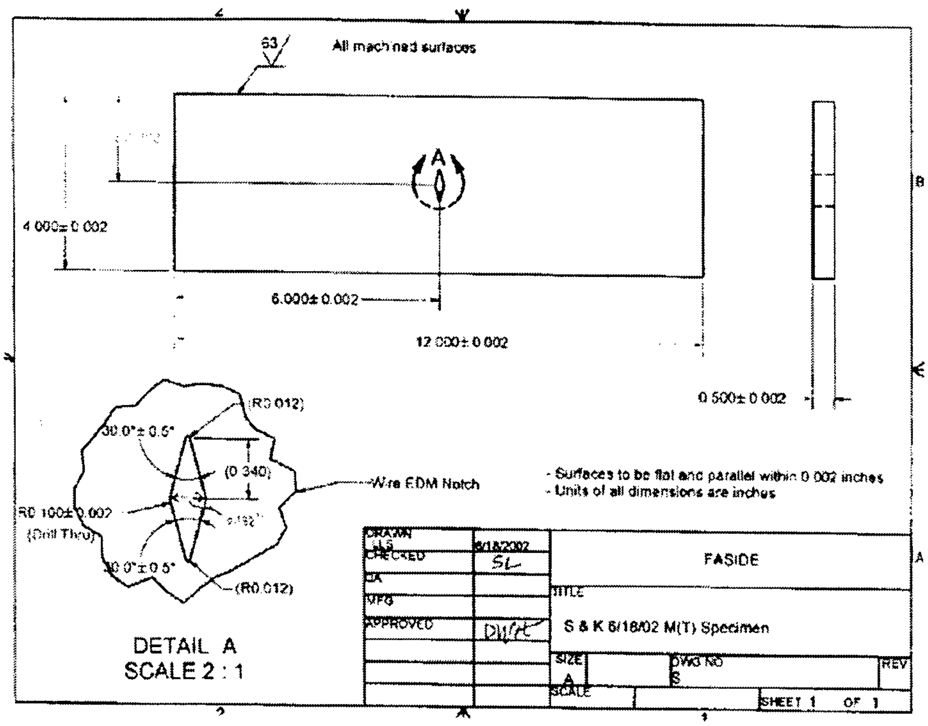

Figure 3: Wide 7075-T651 specimens with diamond-shaped EDM notch, designed by SKT

Table 1: Test matrix for wide 7075-T651 specimens with diamond-shaped EDM notch

Specimen #	Width mm (inch)	Thickness mm (inch)	Spectrum	1.0 spectrum multiplication factor
WDS-1	101.6 (4.0)	12.7 (0.5)	Full	14.24
WDS-2	101.6 (4.0)	12.7 (0.5)	Full	14.24
WDS-3	101.6 (4.0)	12.7 (0.5)	Full	14.24
WDS-4	101.6 (4.0)	12.7 (0.5)	Truncated	14.24
WDS-5	101.6 (4.0)	12.7 (0.5)	Truncated	14.24
WDS-6	101.6 (4.0)	12.7 (0.5)	Truncated	14.24
WDS-7	101.6 (4.0)	12.7 (0.5)	CA	-20/+12 ksi 7Hz
WDS-8	101.6 (4.0)	12.7 (0.5)	CA	-20/+12 ksi 7Hz

Before the specimens could be tested, they had to be pre-cracked to create a natural starter crack. Starting from the EDM diamond shaped notch, the specimens were pre-cracked to a final crack size of approximately 2a = 30.48 mm (1.2"). Per FASIDE drawing, Figure 3, the initial starter notch is a=0.352", hence the pre-crack length is 0.248" on each side.

The specimens were pre-cracked at approximately 50% of the largest tensile stress seen in the spectrum. Since the spectra for WDS-1 through WDS-8 were normalized, with a 1.0 load that corresponds to 14.24 ksi (98.18 MPa), WS 360, it was decided to use a maximum stress level during pre-cracking of 50 MPa (7.25 ksi), with an R-ratio of 0.05.

The first cycle in both the full and the truncated spectrum is 0.696797 x 14.24 ksi = 9.92 ksi (68.4 MPa). By choosing a pre-crack level of 50 MPa (7.25 ksi), no large plastic zones will be created that would affect subsequent spectrum or constant amplitude (CA) test results.

Using a pre-crack stress level of 50 MPa (7.25 ksi) leads to a stress intensity factor at the tip of the starter notch of 7.63 ksi√inch (8.38 MPa√m). With a threshold of approximately ΔK = 3 ksi√inch, this stress level should initiate a crack from the notch. Pre-cracking was done using small cycle intervals to be able to stop the pre-cracking at the desired crack size.

Two specimens were tested with constant amplitude fatigue loading, where the highest tensile stress was 82.7 MPa (+12 ksi), and the highest compressive stress was 137.9 MPa (-20 ksi), therefore an R-ratio of -1.67. These tests were run at a frequency of 7 Hz.

2.2.2 Narrow 7075-T651 Specimens, 0.5" Thick

Four narrow specimens, N1 through N4, were tested to verify that the truncation of the spectrum does not significantly affect the crack growth results. The reason for testing these additional specimens was that the starter notch in the wide specimens was large, which resulted in a very short crack growth life (approximately 1.5 spectrum blocks).

To be able to validate the spectrum truncation over a larger crack growth life, the decision was made to make specimens with smaller starter notches, increasing the crack growth life. Ideally, the specimens would have been 101.6 mm (4.0") wide as well but due to the fact that there was only a limited amount of material from the same batch as the specimens in paragraph 2.2.1 available, it was decided to test specimens that were only half the width of the wide specimens.

The four specimens were 50.8 mm (2") wide, 12.7 mm (0.5") thick, and made out of 7075-T651 bare aluminum. Figure 4 shows a drawing of the specimens. As can be seen, the narrow specimens had a central hole that was reamed after pre-drilling to the final dimension of 3.175 mm (0.125") in diameter. Table 2 shows the test matrix for these specimens.

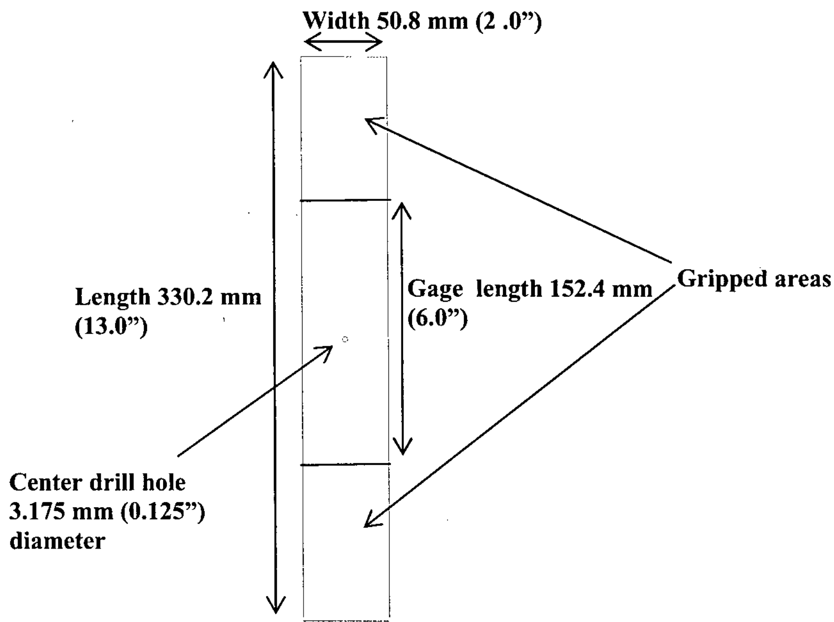

Figure 4: Narrow 7075-T651 specimen with drill hole/corner-crack starter notch

Table 2: Test matrix for narrow 7075-T651 specimen with drill hole/corner-crack starter notch

Specimen #	Width mm (inch)	Thickness mm (inch)	Spectrum	1.0 spectrum multiplication factor
[redacted]	50.8 (2.0)	12.7 (0.5)	Full	16.8
N2	50.8 (2.0)	12.7 (0.5)	Full	16.8
N3	50.8 (2.0)	12.7 (0.5)	Truncated	16.8
N4	50.8 (2.0)	12.7 (0.5)	Truncated	16.8

Since the starter hole in the narrow specimens is much smaller than the EDM notch for the wide specimens, it was more difficult to pre-crack these specimens. First a small corner cut with a razor blade was made on one side of the drill hole. From there, a natural crack is formed using constant amplitude fatigue pre-cracking.

The spectrum tests were run with a spectrum multiplication factor of 16.8 (the 1.0 maximum tensile stress corresponds to 16.8 ksi (115.8 MPa), as can be seen in Table 2. This multiplication factor is the value for wing station 320.

It was decided to use a pre-crack stress level of 110.3 MPa (16 ksi), R=0.05 to initiate the crack and then step down the stress level to 77.2 MPa (11.2 ksi), R=0.05 and reinitiate the crack once more. The latter of the two stress levels is 67% of the maximum tensile load in the spectrum, and with a first cycle in the spectrum of 69.7% of the maximum tensile stress in the spectrum, the pre-crack level stays below the initial cycle in the spectrum.

The goal was to obtain a corner pre-crack that would be 1.27 mm (0.05") long from the edge of the drill hole. It proved to be very difficult to create a starter crack that small that would also continue to grow under the subsequent spectrum loading.

Starter cracks turned out to be larger at the start of the tests, except for specimen N4, see the crack growth data in Appendix A. Specimen N1, marked in red in Table 2, did not show crack nucleation and testing was discontinued.

2.2.3 Wide 2024-T351 Specimens, 0.25" Thick

The third set of specimens was tested to verify the effects of truncation as well as the effects of marker loads added to the spectrum. Since all material for the specimens in paragraphs 2.2.1 and 2.2.2 had been used, it was decided to use 6.35 mm (0.25") thick 2024-T351 bare aluminum. Specimen were 101.6 mm (4.0") wide. Figure 5 shows the dimensions of the specimens. Table 3 shows the test matrix.

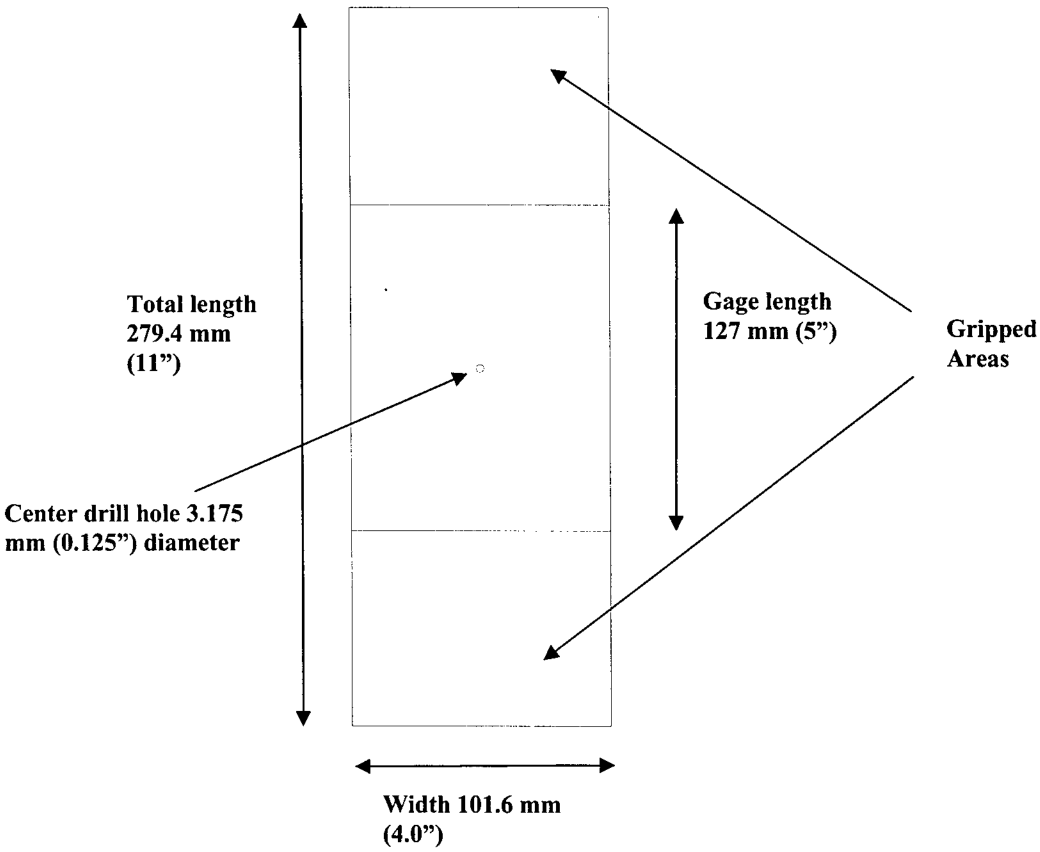

Figure 5: Wide 2024-T351 specimens with drill hole/through-crack starter notch

Table 3: Test matrix for wide 2024-T351 specimens with drill hole/through-crack starter notch

Specimen #	Width mm (inch)	Thickness mm (inch)	Spectrum	1.0 spectrum multiplication factor
T-1	101.6 (4.0)	6.35 (0.25)	Full	16.8
T-2	101.6 (4.0)	6.35 (0.25)	Full	16.8
T-3	101.6 (4.0)	6.35 (0.25)	Full with markers	16.8
[redacted]	101.6 (4.0)	6.35 (0.25)	Full with markers	16.8
T-5	101.6 (4.0)	6.35 (0.25)	Full with markers	16.8
[redacted]	101.6 (4.0)	6.35 (0.25)	Truncated	16.8
[redacted]	101.6 (4.0)	6.35 (0.25)	Truncated	16.8
T-8	101.6 (4.0)	6.35 (0.25)	Truncated	16.8
T-9	101.6 (4.0)	6.35 (0.25)	Truncated	16.8
[redacted]	101.6 (4.0)	6.35 (0.25)	Truncated with markers	16.8
T-11	101.6 (4.0)	6.35 (0.25)	Truncated with markers	16.8
T-12	101.6 (4.0)	6.35 (0.25)	Truncated with markers	16.8

The specimens had a drill hole in the center with a diameter of 3.175 mm (0.125"). A through-cut was made using a jeweler saw on one side of the drill hole. The goal was to obtain a 1.27 mm (0.05") through-the-thickness pre-crack, including the saw cut, from the edge of the drill hole. A constant amplitude fatigue cycle of 89.5 MPa, R-ratio of 0.05, was used to create the pre-cracks, which is approximately 77% of the maximum tensile load in the spectrum.

The spectrum tests were run with a spectrum multiplication factor of 16.8 (the 1.0 maximum tensile stress corresponds to 16.8 ksi (115.8 MPa) as can be seen in Table 2. This multiplication factor is the value for wing station 320.

The goal was to test three specimens per test variable. In case two out of three specimens for each variable showed consistent results, the third test was skipped, or additional tests were performed until two consistent results were obtained for that variable.

The specimens marked in red in Table 3, T-4, T-6, T-7 and T-10, showed asymmetric pre-crack nucleation for the front and back side of the specimens. However, spectrum tests were still performed after pre-cracking and the crack growth data can be found in Appendix A.

3. Test Procedures

3.1 General Procedures

3.1.1 Fatigue Machines

The machines used were MTS 810 55 kips and 110 kips hydraulic test frames, with Test Star II software. All the specimens were clamped in hydraulic wedges (2" wide wedges for the narrow specimens and 4" wide wedges for the wide specimens). Since the specimens are completely clamped, it follows from ASTM E-647 that the minimum gage length should be 1.2W, therefore at least 121.92 mm (4.8") for the wide specimens and a minimum of 60.96 mm (2.4") for the narrow specimens. Since the gage length was a minimum of 127 mm (5.0") for the thin specimens and 152.4 mm (6.0") for all other specimens, this requirement was easily met.

Before starting the pre-crack procedure, the machines were tuned using dummy specimens with the same dimensions and made out of the same material as the actual test specimens. To prevent the introduction of unwanted plasticity, tuning was not done using the actual test specimens.

3.1.2 Measurements

The crack tips were measured using optical traveling microscopes. All 4 crack tips, left, right, back and front, need to be measured, to assure symmetric crack growth.

The ASTM requirement E-647-00 paragraph 8.8.3 states:

- the difference between the crack on front and back side of the specimen must be smaller than 0.25B, where B is the thickness of the specimen,
- or the difference between the left and right crack tip of a M(T) specimen measured from the specimen centerline must be smaller than 0.025W, where W is the width of the specimen and the average of the front and back crack is used for each crack.

Since for the narrow specimens the starter crack is a corner crack on one side of the drill hole, these requirements are not applicable.

3.2 Test Procedures Wide 7075-T651 Specimens, 0.5" Thick

Before starting the fatigue tests, width and thickness of each specimen were carefully measured. From this, the cross sectional area was calculated, which was then used to calculated the load necessary to obtain the desired far field stress. It was decided to control the fatigue machine in ramp rate control, with a rate of 300 kN/sec. This means that the machine will change loads at this rate, therefore taking more time to cycle through a larger cycle.Initial pilot testing done by the University of Utah, Department of Mechanical Engineering, showed that the crack growth life for specimens subjected to the full spectrum was in the range of 3 to 4 passes. Taking one measurement per pass would result in only 4 data points for an a-N curve, which seemed insufficient for these specimens.

To get more data points for the wide specimens, the spectrum block was split into 10 nearly equivalent parts. The first cycle in the spectrum (0.696797 normalized) occurs frequently in the spectrum. It was therefore chosen to split the block up at this tensile load, at approximately every 10% of the block.

Crack measurements were taken by applying a static load to open the crack. This way a more accurate measurement can be made. However, it should be avoided to introduce arbitrary loads into the spectrum to open the crack since this could affect the subsequent crack growth. Thus, measurements were taken at the beginning of each sub-block, and a load of 0.696797 times the maximum tensile load in the spectrum (which is the first cycle in each sub-block) was applied for a short duration.

3.3 Test Procedures Narrow 7075-T651 Specimens, 0.5" Thick

As was the case with the specimens in paragraph 3.2, the width and thickness of each specimen were carefully measured to calculate the cross sectional area, which was then used to calculated the load necessary to obtain the desired far field stress. The fatigue machine was ramp rate controlled, with a rate of 300 kN/sec. Since the starter cracks for these specimens was smaller than for specimens WDS-1 through WDS-8, the spectrum passes/blocks were not split into 10 sub-blocks, and crack size measurements were taken after each complete spectrum pass. The crack measurements were taken by applying a static load of 0.696797 times the maximum tensile load in the spectrum (which is the first cycle in each block), for a short duration.

3.4 Test Procedures Wide 2024-T351 Specimens, 0.25" Thick

As was the case with the other specimens, the width and thickness of each specimen were carefully measured to calculate the cross sectional area, which was then used to calculated the load necessary to obtain the desired far field stress. The fatigue machine was ramp rate controlled, with a rate of 250 kN/sec. Crack size measurements were taken after each complete spectrum pass. The crack measurements were taken by applying a static load of 50 kN (11.24 kips) for a short duration, which is approximately 67% of the maximum tensile load in the spectrum and below the first cycle in the spectrum.

4. Test Results and Discussion

4.1 Test Results Wide 7075-T651 Specimens, 0.5" Thick

Figure 6 shows the crack growth curves for specimens WDS-1 through WDS-6. Since the crack was tracked on both sides of the specimen, curves for both the front and back side are shown. Also note that the average (half) crack size for each side has been plotted. The *a-N* data for all specimens can be found in appendix A.1.

As can be seen from Figure 6, specimens WDS-2 and WDS-3 showed fairly consistent results, specimen WDS-1 showed significantly faster crack growth. Specimens WDS-5 and WDS-6 were consistent as well, WDS-4 showed faster crack growth.

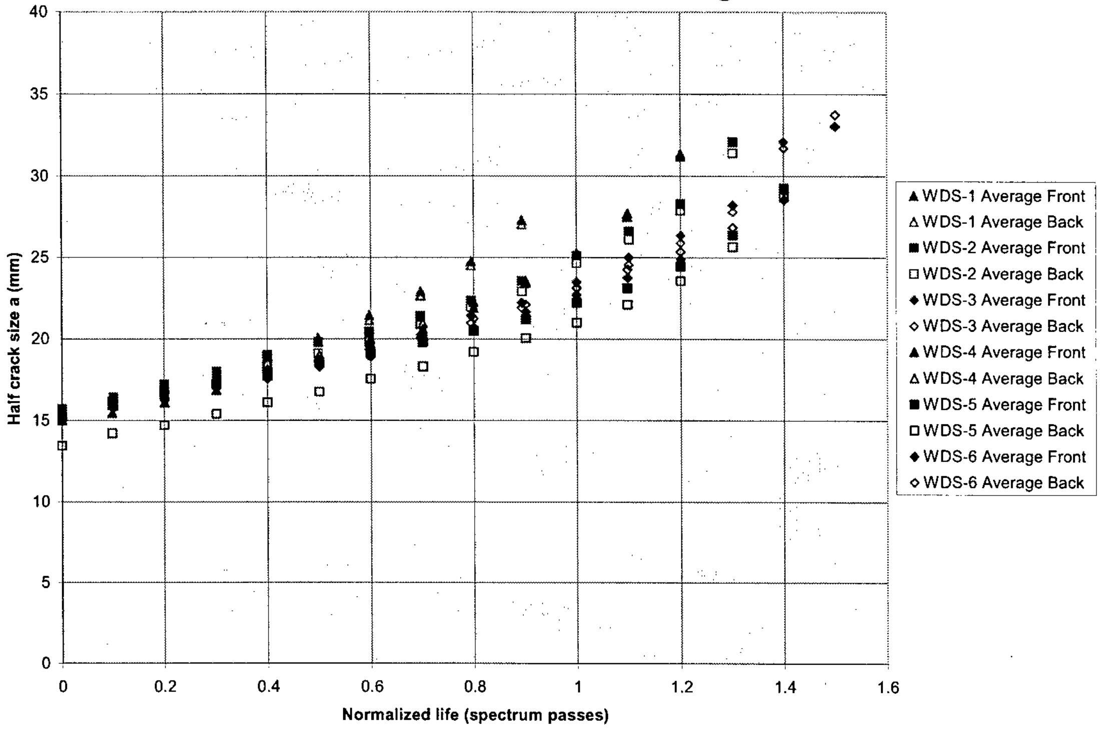

Figure 6: Crack growth curves for specimens WDS-1 through WDS-6, full spectrum (red) compared to truncated spectrum (blue)

When excluding specimens WDS-1 and WDS-4 from the plot, see Figure 7, it can be seen that specimenWDS-3, tested with the full spectrum, showed results that were very close to the truncated spectrum specimens. Specimen WDS-2 was slightly faster. However, realize that only up to 15% of one full aircraft life time has been tested (1.5 spectrum passes at the most for specimen WDS-6), the crack growth curves could potentially diverge more if the specimens could have been tested over a longer crack growth life.

Figure 8 shows crack growth rates (converted to rates per full block) as function of crack size. It can be seen that there is quite some scatter in the results, especially in the smaller crack size ranges. It was therefore decided to test additional specimens that will be discussed in the following two paragraphs.

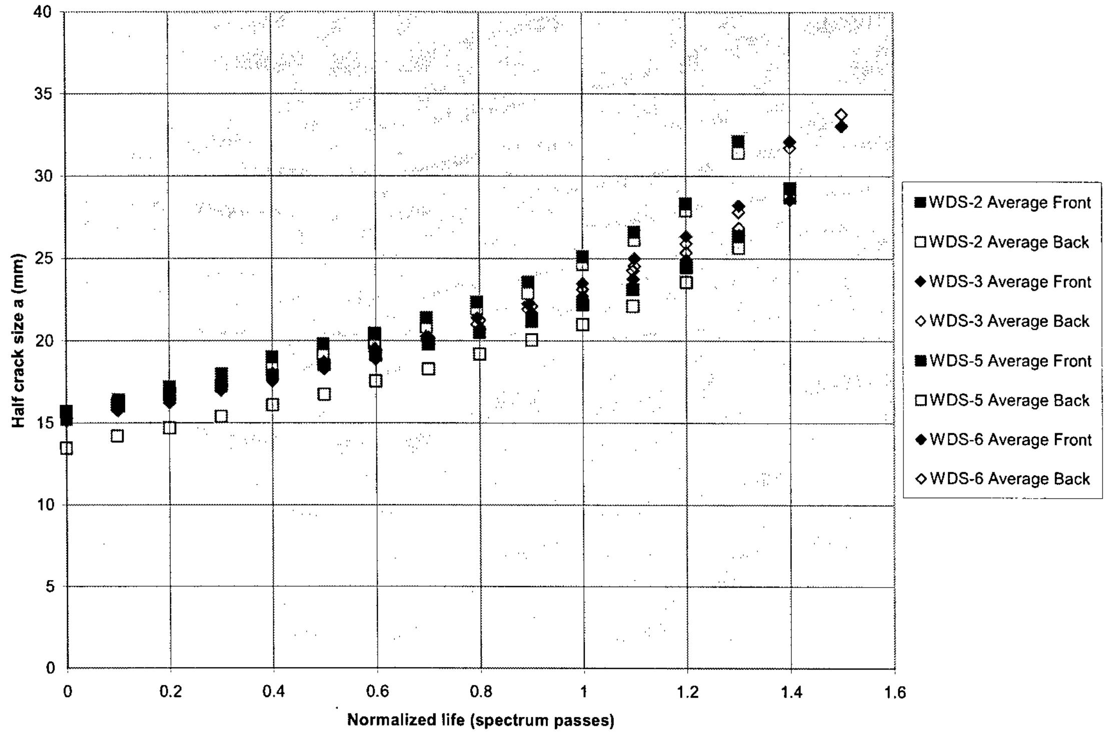

Figure 7: Crack growth curves for specimens tested with full spectrum (red) and truncated spectrum (blue), WDS-1 and WDS-4 excluded

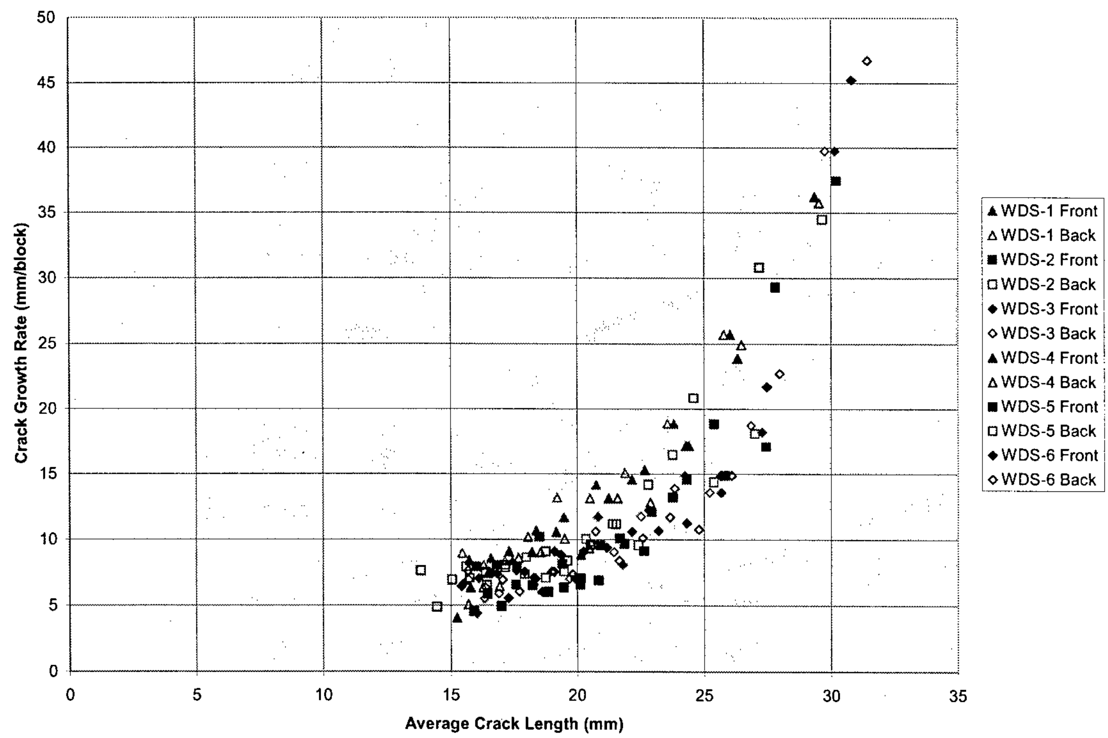

Figure 8: Crack growth rates for specimens WDS-1 through WDS-6, full spectrum (red) compared to truncated spectrum (blue)

4.2 Test Results Narrow 7075-T651 Specimens, 0.5" Thick

Crack sizes were measured only on the front side of the specimen since the starter crack was a corner crack on one side of the drill hole. Left-Right measurements were taken from the vertical centerline of the specimen. Therefore, the total crack size that is plotted in Figure 9 includes the diameter of the drill hole. Note that no measurements are available for the second dimension (into the material) of the corner crack.

Since the side of the drill hole without the saw-cut/pre-crack nucleates differently for each specimen, data is only plotted up to the moment of crack nucleation on the non-pre-cracked side of the drill hole. However, all crack growth data that was collected can be found in appendix A.2.

As can be seen from Figure 9, crack growth data was obtained for significantly smaller crack size range than for specimens WDS-1 through WDS-6. Also note that a total of 12 spectrum passes were tested. As can be seen from the graph, the results for the full spectrum specimen N2 are very similar to the results for the truncated spectrum specimens N3 and N4. Unfortunately, specimen N1 did not develop a crack during pre-cracking, not even after raising the pre-crack stress level. Apparently, there was too much plasticity introduced when making the notch using a razor blade.

Although only a limited amount of specimens was tested due to material availability, and no data was obtained in the short crack regime (crack length on the order of the grain size), the data in the long crack regime shows no noticeable effect as a result of spectrum truncation.

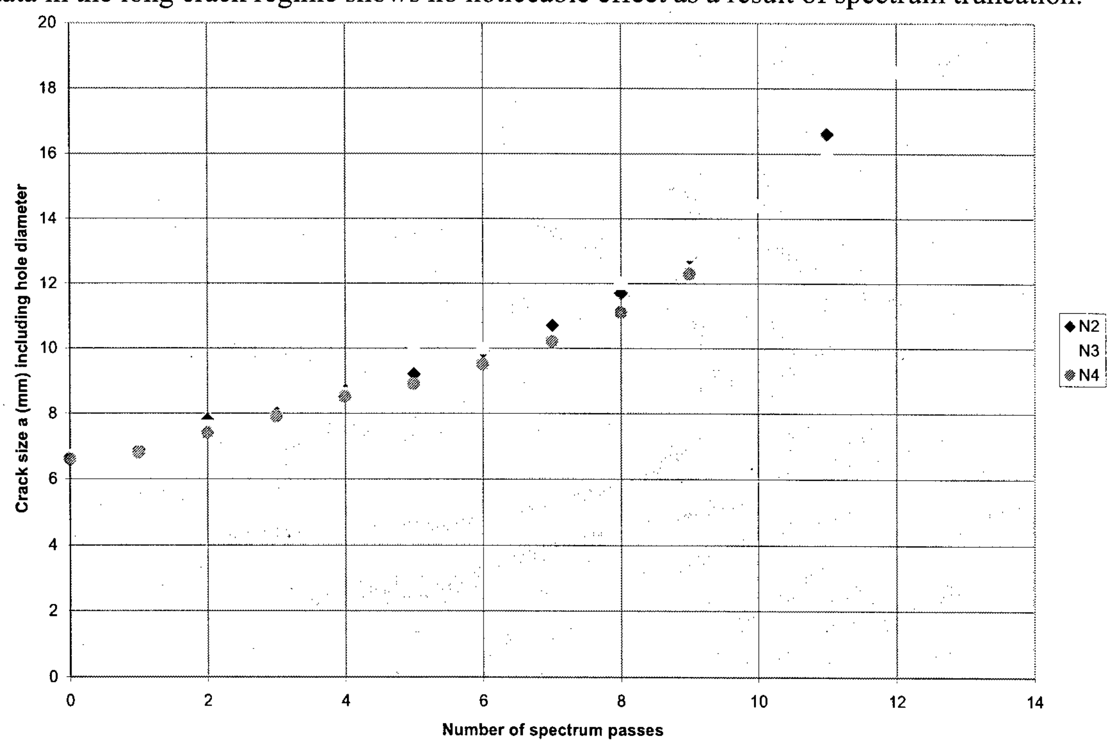

Figure 9: Crack growth curves for specimens N2 through N3, full spectrum (N2) compared to truncated spectrum (N3 and N4)

4.3 Test Results Wide 2024-T351 Specimens, 0.25" Thick

Crack sizes were measured on both the front and the back side of the specimen since the starter crack was a through crack on one side of the drill hole. Left-Right measurements were taken from the vertical centerline of the specimen. Therefore, the total crack sizes that are plotted in the figures in this paragraph include the diameter of the drill hole.

Since the side of the drill hole without saw-cut/pre-crack nucleates differently for each specimen, data is only plotted up to the moment of crack nucleation on the non-pre-cracked side of the drill hole. However, all crack growth data that was collected can be found in appendix A.3.

Figures 10 through 13 show the crack growth results for each variable that was tested. Only curves for two consistent specimens are shown. All results, including the results of specimens not shown in this paragraph can be found in appendix A.3.

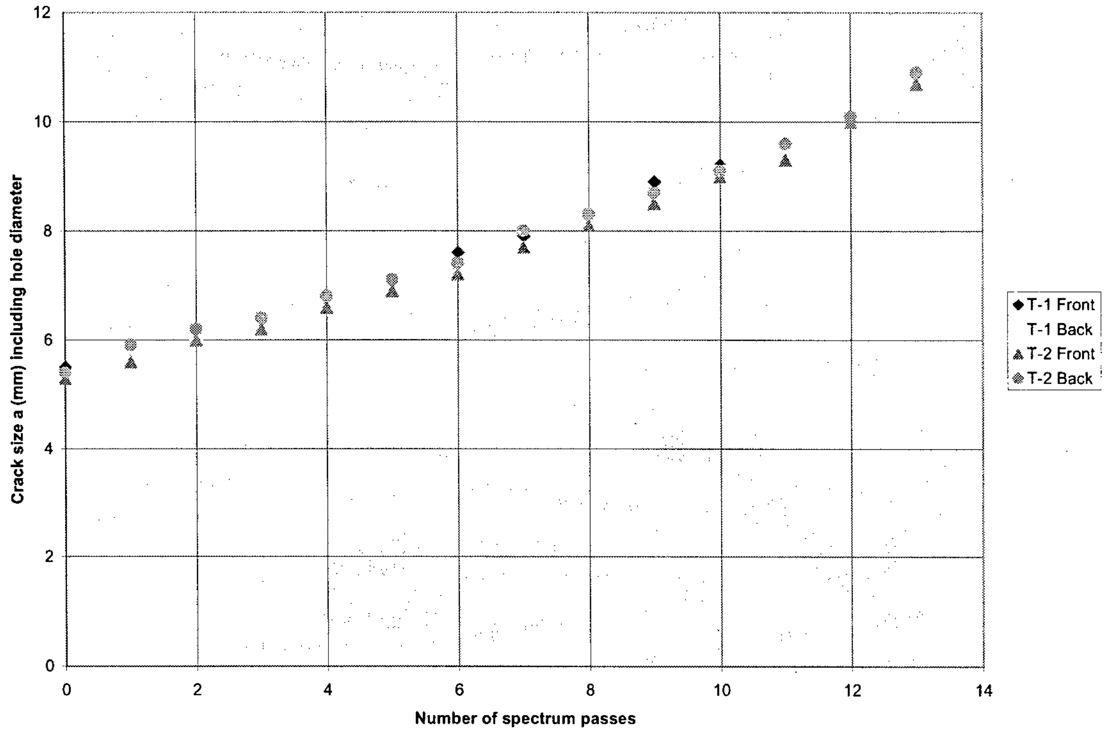

Figure 10: Crack growth curves for specimens T-1 and T-2, full spectrum

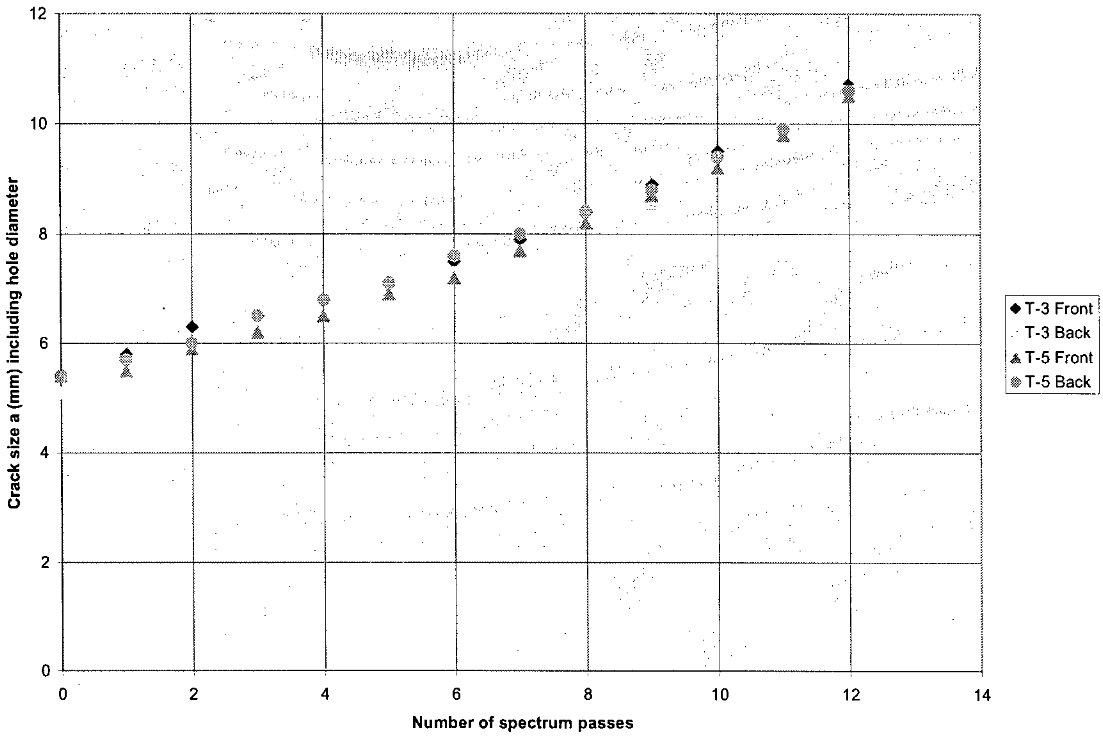

Figure 11: Crack growth curves for specimens T-3 and T-5, full spectrum including marker loads

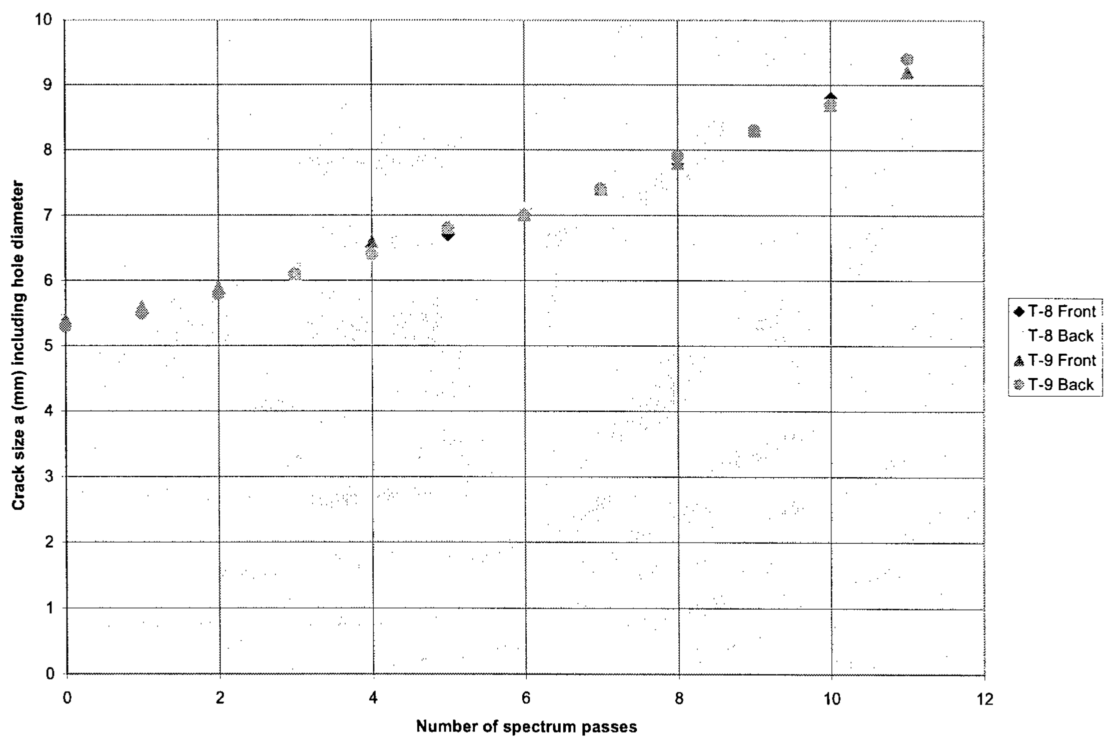

Figure 12: Crack growth curves for specimens T-8 and T-9, truncated spectrum

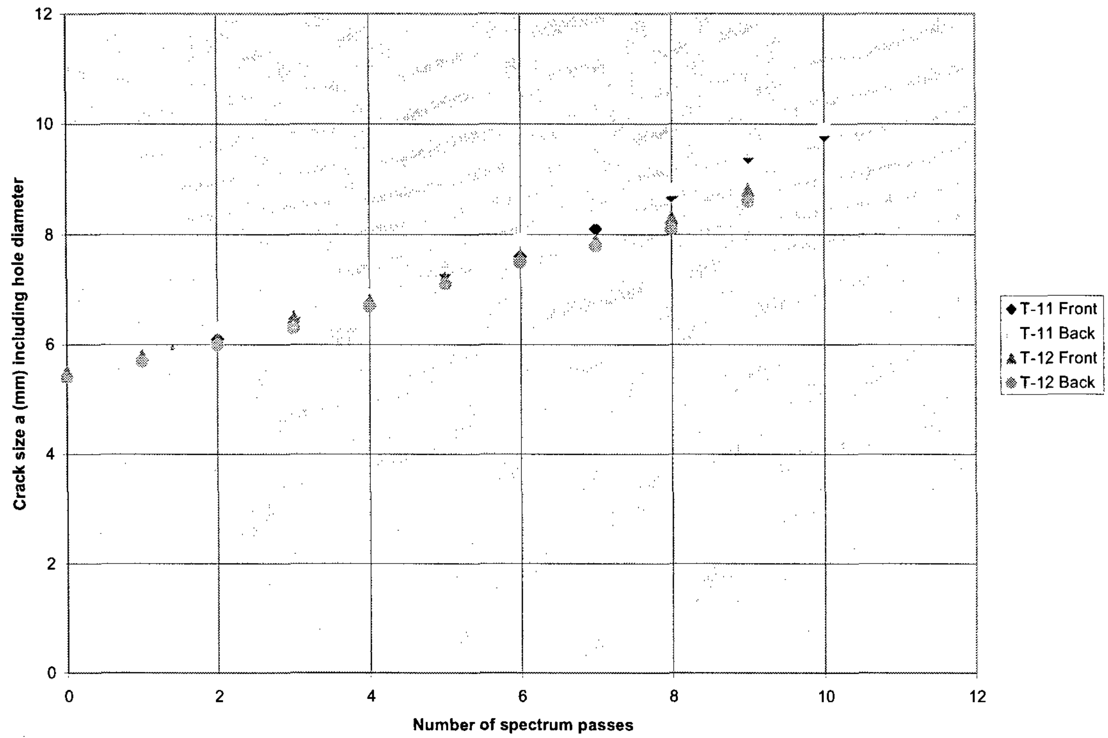

Figure 13: Crack growth curves for specimens T-11 and T-12, truncated spectrum including marker loads

A comparison of the specimens tested with the full and truncated spectrum can be seen in Figure 14. Specimens were tested well over one full aircraft life time and there is no or very minimal effect on crack growth from truncation.

Figure 15 shows crack growth results for specimens tested with the full spectrum, and with the full spectrum including marker loads. It can be seen that the specimens including the marker loads will grow slightly faster after approximately 80% of one full life time has been tested but it must be said that the differences are very minimal.

Figure 16 shows crack growth results for specimens tested with the truncated spectrum and with the truncated spectrum including marker loads. Differences between the two types of specimens are now larger, especially for specimen T-11 at larger crack sizes. Results for specimen T-12 remain close to the results for the specimens tested with the truncated spectrum.

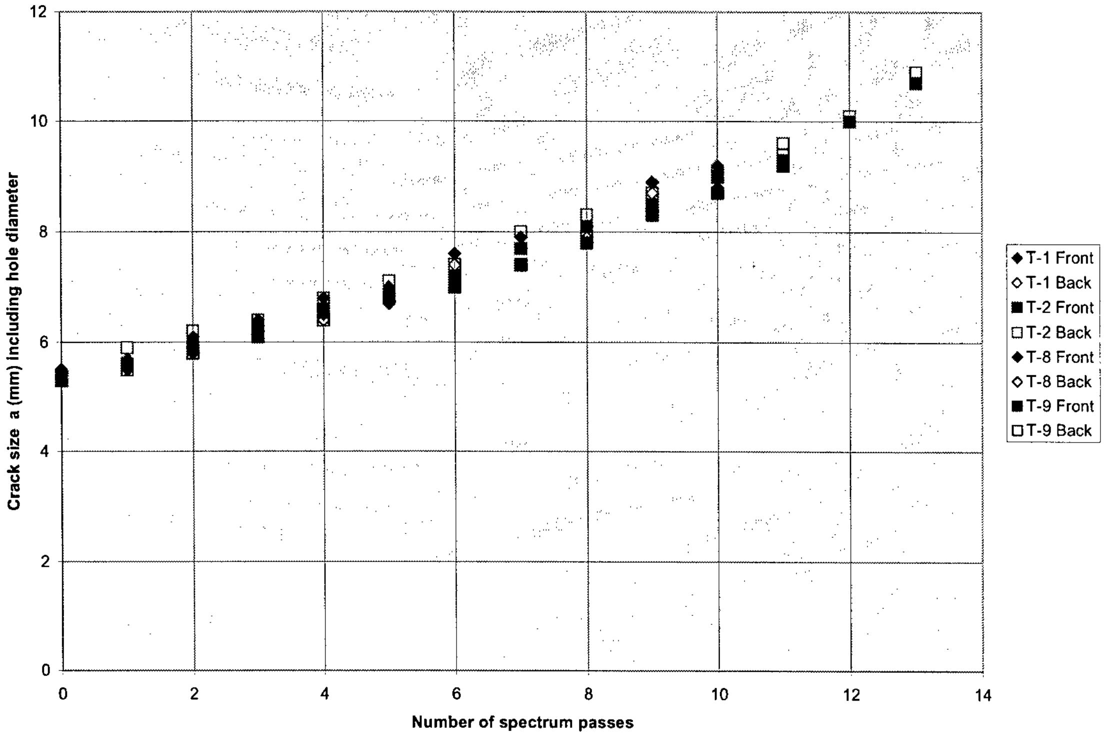

Figure 14: Crack growth curves for specimens with full (red) and truncated spectrum (blue)

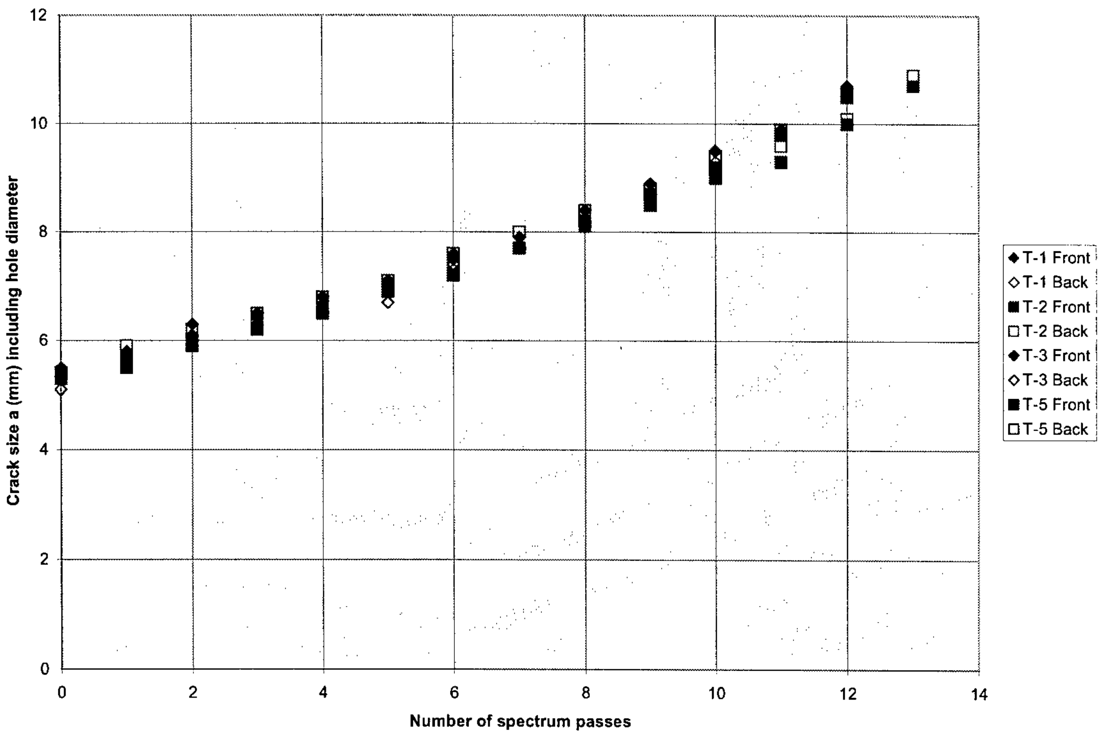

Figure 15: Crack growth curves for specimens with full spectrum (red) and full spectrum including marker loads (blue)

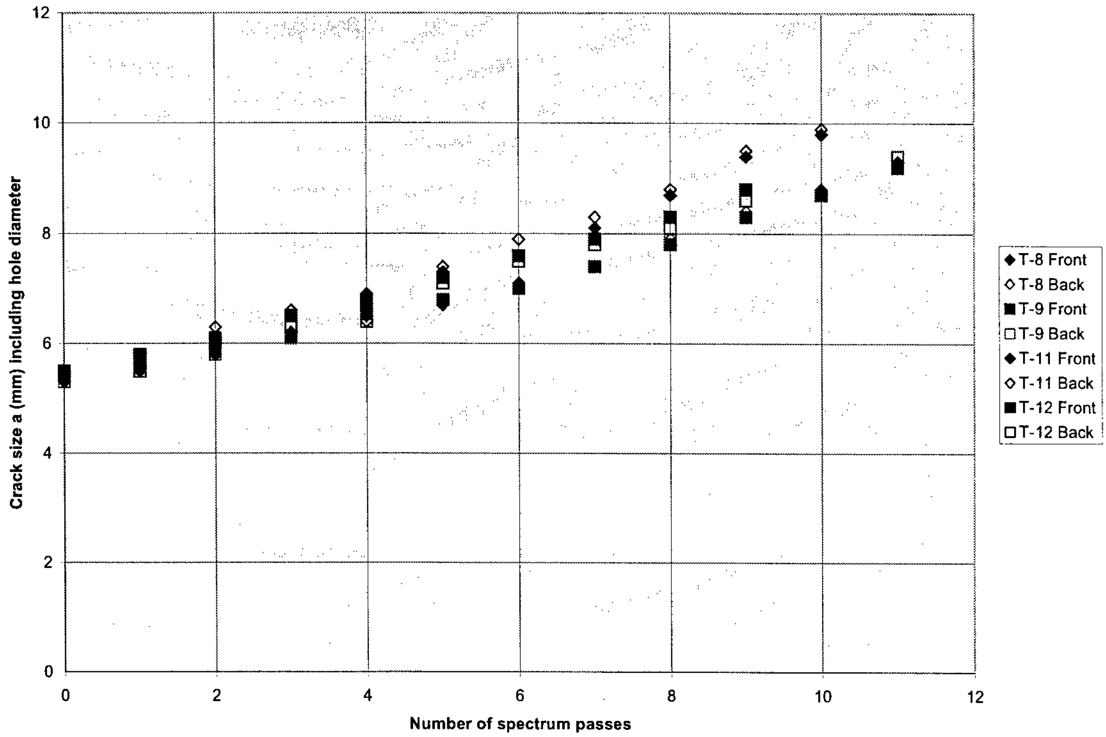

Figure 16: Crack growth curves for specimens with truncated spectrum (red) and truncated spectrum including marker loads (blue)

5. Conclusions

Results from the 4" wide 7075-T651 specimens, 0.5" thick, with an EDM notch showed crack growth data that tended to indicate that truncation of the spectrum had some crack growth reducing effect. However, since the starter notch was quite large, only up to 15% of one aircraft life time could be tested. Crack growth became non-linear as the crack size grew over 50% of the specimen width and differences between the full and truncated spectrum specimens became more significant. Results from these tests did not allow for a conclusive decision on whether specimen truncation had a crack growth altering effect.

Testing of additional 2" narrow 7075-T651 specimens, 0.5" thick, with a small drill hole and corner crack allowed for testing over a larger crack growth life, up to 1.2 aircraft life times. Although only a limited amount of material was available for testing, and no data was obtained in the short crack regime (crack length on the order of the grain size), the data in the long crack regime shows no noticeable effect as a result of spectrum truncation.

Testing of 4" wide 2024-T351, 0.25" thick, specimens showed no significant effect of spectrum truncation on crack growth, even after testing well over 1 aircraft life time. Marker loads that were introduced in the full spectrum showed only a negligible effect on crack growth. However, marker loads that were introduced in the truncated spectrum showed a larger effect on crack growth.

Acknowledgements

We would like to acknowledge the Aging Aircraft Support Squadron, Aeronautical Systems Center (ASC/AASS), Wright-Patterson AFB for funding this work.

Appendix A: Crack Growth Data

A.1 Wide 7075-T651 Specimens with Diamond-Shaped EDM Notch, 0.5" Thick

Left-Right measurements are taken from the vertical centerline of the specimen. Therefore, the length of the EDM notch is included. Note that the left crack tip on the front side of the specimen is corresponding to the right crack tip on the back side of the specimen.

Table 4: Crack growth data front side of WDS-1

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	0	15.2	15.4	15.3
94430	0.100732	16	16.3	16.15
187582	0.2001	17	17	17
282672	0.301535	17.7	18	17.85
374636	0.399636	18.6	19.2	18.9
466922	0.498081	19.9	20.2	20.05
559598	0.596941	20.9	22	21.45
652906	0.696476	22.6	23.2	22.9
744848	0.794554	24.2	25.3	24.75
837842	0.893753	26.8	27.8	27.3

Table 5: Crack growth data back side of WDS-1

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	0	14.8	15.2	15
94430	0.100732	15.8	16	15.9
187582	0.2001	16.8	16.6	16.7
282672	0.301535	17.6	17.5	17.55
374636	0.399636	18.6	18.5	18.55
466922	0.498081	19.9	19.8	19.85
559598	0.596941	21.3	21	21.15
652906	0.696476	22.7	22.6	22.65
744848	0.794554	24.8	24.2	24.5
837842	0.893753	27.3	26.8	27.05

Table 6: Crack growth data front side of WDS-2

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	0	15.8	15.4	15.6
94430	0.100732	16.7	16.1	16.4
187582	0.2001	17.4	17	17.2
282672	0.301535	18.2	17.8	18
374636	0.399636	19.2	18.8	19
466922	0.498081	20	19.6	19.8
559598	0.596941	20.8	20.1	20.45
652906	0.696476	21.6	21.2	21.4
744848	0.794554	22.4	22.3	22.35
837842	0.893753	23.7	23.4	23.55
937442	1	25.2	25	25.1
1031872	1.100732	26.7	26.5	26.6
1125024	1.2001	28.4	28.2	28.3
1220114	1.301535	31.8	32.4	32.1

Table 7: Crack growth data back side of WDS-2

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	0	15.1	15.3	15.2
94430	0.100732	15.9	16.1	16
187582	0.2001	16.6	16.9	16.75
282672	0.301535	17.3	17.8	17.55
374636	0.399636	18.1	18.7	18.4
466922	0.498081	18.9	19.3	19.1
559598	0.596941	19.6	20.1	19.85
652906	0.696476	20.7	21	20.85
744848	0.794554	21.8	22.1	21.95
837842	0.893753	22.8	23	22.9
937442	1	24.5	24.8	24.65
1031872	1.100732	26	26.2	26.1
1125024	1.2001	27.8	28	27.9
1220114	1.301535	31.5	31.3	31.4

Table 8: Crack growth data front side of WDS-3

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	0	15.3	14.9	15.1
94430	0.100732	16	15.5	15.75
187582	0.2001	16.7	16.2	16.45
282672	0.301535	17.4	17	17.2
374636	0.399636	18.1	17.8	17.95
466922	0.498081	18.8	18.5	18.65
559598	0.596941	19.8	19.3	19.55
652906	0.696476	20.4	20.1	20.25
744848	0.794554	21.6	21.2	21.4
837842	0.893753	22.4	22	22.2
937442	1	23.7	23.3	23.5
1031872	1.100732	25.1	24.9	25
1125024	1.2001	26.4	26.3	26.35
1220114	1.301535	28.2	28.2	28.2
1312078	1.399636	32	32.2	32.1

Table 9: Crack growth data back side of WDS-3

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	0	15.4	15.3	15.35
94430	0.100732	16.1	16	16.05
187582	0.2001	16.7	16.5	16.6
282672	0.301535	17.2	17.2	17.2
374636	0.399636	18	17.9	17.95
466922	0.498081	18.6	18.6	18.6
559598	0.596941	19.3	19.4	19.35
652906	0.696476	20	20.1	20.05
744848	0.794554	20.9	21.1	21
837842	0.893753	21.8	22	21.9
937442	1	23.2	23.1	23.15
1031872	1.100732	24.6	24.5	24.55
1125024	1.2001	25.9	25.9	25.9
1220114	1.301535	27.8	27.8	27.8
1312078	1.399636	31.8	31.6	31.7

Table 10: Crack growth data front side of WDS-4

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	0	14.5	15.6	15.05
25940	0.098366	15	15.9	15.45
52870	0.200487	15.8	16.4	16.1
79450	0.30128	16.7	17	16.85
105540	0.400215	17.7	17.8	17.75
131780	0.499719	18.6	18.7	18.65
157988	0.599102	19.7	19.7	19.7
184812	0.700821	20.6	20.6	20.6
210900	0.799748	22.2	21.6	21.9
237616	0.901057	23.7	23.2	23.45
263708	1	25.2	25.1	25.15
289648	1.098366	27.8	27.2	27.5
316578	1.200487	32.1	30.3	31.2

Table 11: Crack growth data back side of WDS-4

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	0	15.9	15	15.45
25940	0.098366	16.3	15.6	15.95
52870	0.200487	16.8	16.4	16.6
79450	0.30128	17.3	17.2	17.25
105540	0.400215	18.1	18.1	18.1
131780	0.499719	19.1	18.9	19
157988	0.599102	20	20	20
184812	0.700821	20.9	21	20.95
210900	0.799748	22.2	22.3	22.25
237616	0.901057	23.4	23.7	23.55
263708	1	25.1	25.4	25.25
289648	1.098366	27.4	28	27.7
316578	1.200487	30.7	32	31.35

Table 12: Crack growth data front side of WDS-5

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	0	15.8	15.6	15.7
25940	0.098366	16.4	15.9	16.15
52870	0.200487	16.9	16.6	16.75
79450	0.30128	17.4	17.1	17.25
105540	0.400215	18	17.8	17.9
131780	0.499719	18.7	18.4	18.55
157988	0.599102	19.3	19	19.15
184812	0.700821	19.9	19.7	19.8
210900	0.799748	20.5	20.5	20.5
237616	0.901057	21.3	21.1	21.2
263708	1	22.3	22.1	22.2
289648	1.098366	23.2	23	23.1
316578	1.200487	24.6	24.3	24.45
343158	1.30128	26.8	25.9	26.35
369248	1.400215	29.9	28.6	29.25

Table 13: Crack growth data back side of WDS-5

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	0	13.1	13.8	13.45
25940	0.098366	13.8	14.6	14.2
52870	0.200487	14.3	15.1	14.7
79450	0.30128	15	15.8	15.4
105540	0.400215	15.7	16.5	16.1
131780	0.499719	16.3	17.2	16.75
157988	0.599102	17.3	17.8	17.55
184812	0.700821	17.9	18.7	18.3
210900	0.799748	18.8	19.6	19.2
237616	0.901057	19.8	20.3	20.05
263708	1	20.7	21.3	21
289648	1.098366	21.7	22.5	22.1
316578	1.200487	23.2	23.9	23.55
343158	1.30128	25.1	26.2	25.65
369248	1.400215	27.7	29.7	28.7

Table 14: Crack growth data front side of WDS-6

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	0	15.3	15	15.15
25940	0.098366	15.9	15.7	15.8
52870	0.200487	16.4	16.1	16.25
79450	0.30128	17.2	16.8	17
105540	0.400215	17.8	17.3	17.55
131780	0.499719	18.6	18	18.3
157988	0.599102	19.3	18.5	18.9
184812	0.700821	20.1	19.5	19.8
210900	0.799748	21.1	20.3	20.7
237616	0.901057	22	21.3	21.65
263708	1	23.1	22.3	22.7
289648	1.098366	24.1	23.4	23.75
316578	1.200487	25.2	24.6	24.9
343158	1.30128	26.8	26	26.4
369248	1.400215	29	28.1	28.55
395488	1.499719	33.6	32.5	33.05

Table 15: Crack growth data back side of WDS-6

Segments	Normalized life (passes)	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	0	15.3	15.3	15.3
25940	0.098366	16	16.1	16.05
52870	0.200487	16.7	16.7	16.7
79450	0.30128	17.2	17.6	17.4
105540	0.400215	18	18	18
131780	0.499719	18.7	18.7	18.7
157988	0.599102	19.3	19.6	19.45
184812	0.700821	20.1	20.3	20.2
210900	0.799748	21.2	21.3	21.25
237616	0.901057	22	22.2	22.1
263708	1	23.1	23.1	23.1
289648	1.098366	24.2	24.3	24.25
316578	1.200487	25.3	25.4	25.35
343158	1.30128	26.8	26.9	26.85
369248	1.400215	29.1	29.1	29.1
395488	1.499719	33.6	33.9	33.75

Table 16: Crack growth data front side of WDS-7

Cycles	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	15.6	14.8	15.2
1000	16.8	15.9	16.35
1500	17.6	16.4	17
2000	18.2	17	17.6
2500	18.7	17.7	18.2
3000	19.3	18.6	18.95
3500	19.9	19.8	19.85
3750	20.3	20.1	20.2
4000	20.9	20.3	20.6
4250	21.5	20.8	21.15
4500	22.1	21.2	21.65
4750	22.7	22	22.35
5000	23.4	22.4	22.9
5250	24.6	22.9	23.75
5500	25.7	23.4	24.55
5750	26.7	24.4	25.55
6000	27.7	25.9	26.8
6250	29.6	27.8	28.7
6500	31.9	30.7	31.3

Table 17: Crack growth data back side of WDS-7

Cycles	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	14.7	16.1	15.4
1000	15.9	17.4	16.65
1500	16.4	17.9	17.15
2000	17.1	18.4	17.75
2500	17.9	19.2	18.55
3000	18.6	20	19.3
3500	19.3	20.8	20.05
3750	19.9	21.1	20.5
4000	20.3	21.4	20.85
4250	21.1	22.4	21.75
4500	21.6	23.2	22.4
4750	22.1	23.9	23
5000	22.7	24.7	23.7
5250	23.4	25.4	24.4
5500	24.7	27.1	25.9
5750	25.7	28.4	27.05
6000	26.8	29.9	28.35
6250	28.3	30.9	29.6
6500	30.3	32.7	31.5

Table 18: Crack growth data front side of WDS-8

Cycles	Left crack (mm)	Right crack (mm)	Average Crack Front (mm)
0	15.2	15.7	15.45
500	16	16.2	16.1
1000	16.7	16.7	16.7
1500	17.3	17.2	17.25
2000	17.7	17.8	17.75
2500	18.1	18.5	18.3
3000	19	19.2	19.1
3500	19.9	20.2	20.05
3750	20.7	20.7	20.7
4000	21.1	21.3	21.2
4250	21.7	21.8	21.75
4500	22.3	22.6	22.45
4750	23.2	23.2	23.2
5000	23.9	23.8	23.85
5250	25.1	24.3	24.7
5500	26.7	25.1	25.9
5750	27.8	26.2	27
6000	28.9	27.7	28.3

Table 19: Crack growth data back side of WDS-8

Cycles	Left crack (mm)	Right crack (mm)	Average Crack Back (mm)
0	14.7	15.7	15.2
500	15.2	16	15.6
1000	15.8	16.5	16.15
1500	16.2	17.2	16.7
2000	16.8	17.8	17.3
2500	17.6	18.6	18.1
3000	18.4	19.3	18.85
3500	19.5	20.3	19.9
3750	20	20.7	20.35
4000	20.4	21.3	20.85
4250	21	22	21.5
4500	21.4	22.7	22.05
4750	22.3	23.1	22.7
5000	22.8	23.8	23.3
5250	23.4	26	24.7
5500	24.6	28.4	26.5
5750	25.2	29.8	27.5
6000	26.4	31	28.7

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Crack sizes are only measured on the front side of the specimen since the starter crack was a corner crack on one side of the hole. Left-Right measurements are taken from the vertical centerline of the specimen. Therefore, the total crack size includes the diameter of the drill hole.

Table 20: Crack growth data for specimen N2, full spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)
0	4.7	1.9	6.6
1	5	1.9	6.9
2	5.9	1.9	7.8
3	6.1	1.9	8
4	6.8	1.9	8.7
5	7.3	1.9	9.2
6	8	1.9	9.9
7	8.8	1.9	10.7
8	9.8	1.9	11.7
9	10.9	1.9	12.8
10	12.5	1.9	14.4
11	14.7	1.9	16.6
12	18.7	5.2	23.9

Table 21: Crack growth data for specimen N3, truncated spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)
0	4.8	1.9	6.7
1	5.3	1.9	7.2
2	5.7	1.9	7.6
3	6	1.9	7.9
4	6.7	1.9	8.6
5	7.9	1.9	9.8
6	8.1	1.9	10
7	9.4	1.9	11.3
8	10.1	1.9	12
9	11	1.9	12.9
10	12.5	1.9	14.4
11	14	1.9	15.9
12	16.6	1.9	18.5
13	23.3	6.8	30.1

Table 22: Crack growth data for specimen N4, truncated spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Spectrum Passes	Total Crack Front (mm)
0	3	1.6	4.6		
1	3.1	1.6	4.7		
2	4.1	1.6	5.7		
3	4.3	1.6	5.9		
4	4.8	1.6	6.4		
5	4.8	1.6	6.4		
6	5	1.6	6.6	0	6.6
7	5.2	1.6	6.8	1	6.8
8	5.8	1.6	7.4	2	7.4
9	6.3	1.6	7.9	3	7.9
10	6.9	1.6	8.5	4	8.5
11	7.3	1.6	8.9	5	8.9
12	7.9	1.6	9.5	6	9.5
13	8.6	1.6	10.2	7	10.2
14	9.5	1.6	11.1	8	11.1
15	10.7	1.6	12.3	9	12.3
16	12.2	4	16.2	10	16.2
17	14	5.9	19.9	11	19.9
18	17.4	7.5	24.9	12	24.9

Note that column 6 contains the same data as column 4. After 6 spectrum passes, the crack size for this specimen was the same as the starter crack size for specimens N2 and N3, and therefore a comparison of specimen N4 to specimen N2 and N3 can only be made for the last 12 passes of specimen N4.

A.3 Wide 2024-T351 Specimens, 0.25" Thick

Left-Right measurements are taken from the vertical centerline of the specimen. Therefore, the total crack size includes the diameter of the drill hole. Note that the left crack tip on the front side of the specimen is corresponding to the right crack tip on the back side of the specimen.

Table 23: Crack growth data for specimen T-1, full spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.8	3.7	5.5	3.5	1.8	5.3
1	1.8	3.9	5.7	3.9	1.8	5.7
2	1.8	4.3	6.1	4.2	1.8	6
3	1.8	4.6	6.4	4.5	1.8	6.3
4	1.8	5	6.8	5	1.8	6.8
5	1.8	5.2	7	5.2	1.8	7
6	1.8	5.8	7.6	5.6	1.8	7.4
7	1.8	6.1	7.9	5.9	1.8	7.7
8	1.8	6.3	8.1	6.3	1.8	8.1
9	1.8	7.1	8.9	6.9	1.8	8.7
10	1.8	7.4	9.2	7.3	1.8	9.1
11	2.1	8	10.1	7.9	1.8	9.7
12	2.3	8.7	11	8.6	2.6	11.2
13	3.2	9.3	12.5	9.2	3.2	12.4
14	4.1	10.1	14.2	10.1	4.1	14.2
15	5.1	11.4	16.5	11.4	5.1	16.5
16	6.5	12.9	19.4	12.9	6.5	19.4
17	8.3	14.9	23.2	14.9	8.3	23.2
18	11.2	17.8	29	17.8	11.1	28.9
19	15.3	22	37.3	22.1	15.2	37.3
20	23.5	31	54.5	31.2	23.5	54.7

Table 24: Crack growth data for specimen T-2, full spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.9	3.4	5.3	3.3	2.1	5.4
1	1.9	3.7	5.6	3.8	2.1	5.9
2	1.9	4.1	6	4.1	2.1	6.2
3	1.9	4.3	6.2	4.3	2.1	6.4
4	1.9	4.7	6.6	4.7	2.1	6.8
5	1.9	5	6.9	5	2.1	7.1
6	1.9	5.3	7.2	5.3	2.1	7.4
7	1.9	5.8	7.7	5.9	2.1	8
8	1.9	6.2	8.1	6.2	2.1	8.3
9	1.9	6.6	8.5	6.6	2.1	8.7
10	1.9	7.1	9	7	2.1	9.1
11	1.9	7.4	9.3	7.5	2.1	9.6
12	1.9	8.1	10	8	2.1	10.1
13	1.9	8.8	10.7	8.8	2.1	10.9
14	1.9	9.4	11.3	9.4	3.4	12.8
15	3.7	10.3	14	10.2	4.6	14.8
16	5.1	11.6	16.7	11.6	5.8	17.4
17	6.9	13.1	20	13.1	7.3	20.4
18	9.1	15.1	24.2	15.2	9.6	24.8
19	12.2	18.3	30.5			
20	17.2	23.2	40.4	23	17.3	40.3
21	29	36.1	65.1	35.9	29.5	65.4

Table 25: Crack growth data for specimen T-3, full spectrum with marker loads

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.7	3.7	5.4	3.5	1.6	5.1
1	1.7	4.1	5.8	4	1.6	5.6
2	1.7	4.6	6.3	4.3	1.6	5.9
3	1.7	4.8	6.5	4.7	1.6	6.3
4	1.7	5.1	6.8	4.9	1.6	6.5
5	1.7	5.4	7.1	5.1	1.6	6.7
6	1.7	5.8	7.5	5.7	1.6	7.3
7	1.7	6.2	7.9	6.1	1.6	7.7
8	1.7	6.7	8.4	6.6	1.6	8.2
9	1.7	7.2	8.9	7.1	1.6	8.7
10	1.7	7.8	9.5	7.7	1.6	9.3
11	1.7	8.2	9.9	8.3	1.6	9.9
12	1.7	9	10.7	9	1.6	10.6
13	2.7	9.8	12.5	9.9	2.8	12.7

Table 26: Crack growth data for specimen T-4, full spectrum with marker loads

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.6	3.7	5.3	2.9	1.8	4.7
1	1.6	4	5.6	3.2	1.8	5
2	1.6	4.2	5.8	3.6	1.8	5.4
3	1.6	4.7	6.3	3.9	1.8	5.7
4	1.6	5	6.6	4.1	1.8	5.9
5	1.6	5.3	6.9	4.6	1.8	6.4
6	1.6	5.6	7.2	4.9	1.8	6.7
7	1.6	5.9	7.5	5.2	1.8	7
8	1.6	6.4	8	5.8	1.8	7.6
9	1.6	6.8	8.4	6.2	1.8	8
10	1.6	7.2	8.8	6.7	1.8	8.5
11	1.6	7.8	9.4	7.2	1.8	9
12	1.6	8.4	10	8	1.8	9.8
13	1.7	9	10.7	8.6	2.1	10.7
14	2.8	9.9	12.7	9.9	3.4	13.3

Table 27: Crack growth data for specimen T-5, full spectrum with marker loads

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.6	3.8	5.4	3.8	1.6	5.4
1	1.6	3.9	5.5	4.1	1.6	5.7
2	1.6	4.3	5.9	4.4	1.6	6
3	1.6	4.6	6.2	4.9	1.6	6.5
4	1.6	4.9	6.5	5.2	1.6	6.8
5	1.6	5.3	6.9	5.5	1.6	7.1
6	1.6	5.6	7.2	6	1.6	7.6
7	1.6	6.1	7.7	6.4	1.6	8
8	1.6	6.6	8.2	6.8	1.6	8.4
9	1.6	7.1	8.7	7.2	1.6	8.8
10	1.6	7.6	9.2	7.8	1.6	9.4
11	1.6	8.2	9.8	8.3	1.6	9.9
12	1.6	8.9	10.5	9	1.6	10.6
13	2.7	10	12.7	9.9	1.6	11.5

Table 28: Crack growth data for specimen T-6, truncated spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.7	3.8	5.5	3	1.8	4.8
2	1.7	4.4	6.1	3.9	1.8	5.7
4	1.7	5	6.7	4.2	1.8	6
6	1.7	5.6	7.3	4.8	1.8	6.6
8	1.7	6.1	7.8	5.4	1.8	7.2
10	1.7	6.7	8.4	6.1	1.8	7.9
12	1.7	7.6	9.3	7.1	1.8	8.9
14	1.7	8.6	10.3	8	1.8	9.8
16	3.7	9.9	13.6	9.3	3.6	12.9
18	5.7	11.9	17.6	11.4	5.9	17.3
20	9.2	15.5	24.7	14.9	9.5	24.4
22	16.9	22.7	39.6	22.3	16.8	39.1

Table 29: Crack growth data for specimen T-7, truncated spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	2	3.3	5.3	3	1.5	4.5
1	2	3.7	5.7	3.3	1.5	4.8
2	2	3.9	5.9	3.7	1.5	5.2
3	2	4.2	6.2	3.8	1.5	5.3
4	2	4.4	6.4	4.1	1.5	5.6
5	2	4.9	6.9	4.5	1.5	6
6	2	5.1	7.1	4.9	1.5	6.4
7	2	5.3	7.3	5.1	1.5	6.6
8	2	5.8	7.8	5.6	1.5	7.1
9	2	5.9	7.9	5.6	1.5	7.1
10	2	6.3	8.3	6.3	1.5	7.8
11	2	6.7	8.7	6.7	1.5	8.2
12	2	7.2	9.2	7.2	1.5	8.7
13	2	7.7	9.7	7.9	1.5	9.4
14	2	8.2	10.2	8.3	1.5	9.8
15	3.2	9.2	12.4			

Table 30: Crack growth data for specimen T-8, truncated spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.6	3.7	5.3	4	1.4	5.4
1	1.6	3.9	5.5	4.2	1.4	5.6
2	1.6	4.2	5.8	4.4	1.4	5.8
3	1.6	4.6	6.2	4.8	1.4	6.2
4	1.6	4.9	6.5	5	1.4	6.4
5	1.6	5.1	6.7	5.4	1.4	6.8
6	1.6	5.5	7.1	5.7	1.4	7.1
7	1.6	5.8	7.4	6	1.4	7.4
8	1.6	6.2	7.8	6.5	1.4	7.9
9	1.6	6.7	8.3	7	1.4	8.4
10	1.6	7.2	8.8	7.3	1.4	8.7
11	1.6	7.7	9.3	7.9	1.4	9.3
12	2.8	8.4	11.2	8.6	2.6	11.2

Table 31: Crack growth data for specimen T-9, truncated spectrum

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.8	3.6	5.4	3.8	1.5	5.3
1	1.8	3.8	5.6	4	1.5	5.5
2	1.8	4.1	5.9	4.3	1.5	5.8
3	1.8	4.3	6.1	4.6	1.5	6.1
4	1.8	4.8	6.6	4.9	1.5	6.4
5	1.8	5	6.8	5.3	1.5	6.8
6	1.8	5.2	7	5.5	1.5	7
7	1.8	5.6	7.4	5.9	1.5	7.4
8	1.8	6	7.8	6.4	1.5	7.9
9	1.8	6.5	8.3	6.8	1.5	8.3
10	1.8	6.9	8.7	7.2	1.5	8.7
11	1.8	7.4	9.2	7.9	1.5	9.4
12	2	7.9	9.9	8.3	1.5	9.8
13	2.9	8.6	11.5	8.9	2.1	11

Table 32: Crack growth data for specimen T-10, truncated spectrum with marker loads

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.8	3.9	5.7	3.4	1.5	4.9
1	1.8	4.2	6	3.8	1.5	5.3
2	1.8	4.6	6.4	4.1	1.5	5.6
3	1.8	4.9	6.7	4.5	1.5	6
4	1.8	5.1	6.9	4.8	1.5	6.3
5	1.8	5.4	7.2	5.2	1.5	6.7
6	1.8	5.8	7.6	5.4	1.5	6.9
7	1.8	6.2	8	6	1.5	7.5
8	1.8	6.6	8.4	6.3	1.5	7.8
9	1.8	7	8.8	6.8	1.5	8.3
10	2.1	7.4	9.5	7.4	1.5	8.9

Table 33: Crack growth data for specimen T-11, truncated spectrum with marker loads

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.7	3.8	5.5	3.8	1.7	5.5
1	1.7	4	5.7	4.1	1.7	5.8
2	1.7	4.4	6.1	4.6	1.7	6.3
3	1.7	4.8	6.5	4.9	1.7	6.6
4	1.7	5.2	6.9	5.2	1.7	6.9
5	1.7	5.6	7.3	5.7	1.7	7.4
6	1.7	5.9	7.6	6.2	1.7	7.9
7	1.7	6.4	8.1	6.6	1.7	8.3
8	1.7	7	8.7	7.1	1.7	8.8
9	1.7	7.7	9.4	7.8	1.7	9.5
10	1.7	8.1	9.8	8.2	1.7	9.9
11	2.4	8.7	11.1	8.9	2.3	11.2

Table 34: Crack growth data for specimen T-12, truncated spectrum with marker loads

Spectrum Passes	Left Crack Front (mm)	Right Crack Front (mm)	Total Crack Front (mm)	Left Crack Back (mm)	Right Crack Back (mm)	Total Crack Back (mm)
0	1.7	3.8	5.5	3.6	1.8	5.4
1	1.7	4.1	5.8	3.9	1.8	5.7
2	1.7	4.4	6.1	4.2	1.8	6
3	1.7	4.8	6.5	4.5	1.8	6.3
4	1.7	5.1	6.8	4.9	1.8	6.7
5	1.7	5.5	7.2	5.3	1.8	7.1
6	1.7	5.9	7.6	5.7	1.8	7.5
7	1.7	6.2	7.9	6	1.8	7.8
8	1.7	6.6	8.3	6.3	1.8	8.1
9	1.7	7.1	8.8	6.8	1.8	8.6
10	1.7	7.7	9.4	7.5	2.3	9.8
11	2	8.3	10.3	8	2.9	10.9